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Development of a semi-active Helmholtz resonator in noise reduction of sound sources

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ABSTRACT

Unwanted noises and loud sounds must be prevented from being transmitted to humans because they generate serious problems in the long term in terms of psychology and physiology. Helmholtz resonators are typically used as passive sound reducers for noise suppression in acoustic systems, such as vehicle exhaust, industry, engine intake manifolds, blowers, and more. It is a simple structure, but its performance is proper for restricting to a narrow band of frequencies due to its geometry. This work presents an adaptive Helmholtz resonator that can continuously change the effective frequency range regarding diverse sound sources. In this way, optimum performance over a constant point is achieved. The system includes a hollow box serving as a Helmholtz resonator, a variable orifice connected to a servomotor, and a controller. The controller receives the sound level and its frequency from the duct via a microphone and then adjusts the orifice area using the servomotor. This simple configuration adjusts the size of the orifice by rotating the butterfly within an effective frequency range based on the sound source characteristics. The experiments demonstrate that sound reduction in frequencies lower than 1000 Hz is achieved effectively, with an approximate decrease of 46%. Moreover, during a test with a pressurized tube connected to an air compressor, the system showed a 30% reduction in sound level. However, at high pressure, the sound

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level reduction is 6.6%. Additionally, an air horn was tested as a sound source connected to the tube. The unbearable sound level is decreased by 28.5% at a high level of air pressure, although there are no significant differences in pressure.

1. Introduction

Mechanical systems often generate unwanted noises, and sometimes, these can be harmful to the human body, causing mental distress. A High level of noise creates serious problems for human operators in industry centers and factories. Thus, commonly, noise attenuation is provided by noise control devices. Most noise controllers work by a passive method, while others actively reduce the noise level. Active noise control is a proper method for controlling low-frequency noise, and it has recently developed into a valuable solution due to its sustainability in various applications, such as the automotive and petroleum industries. Some active noise controllers (AVC) use reversible waves to neutralize the main wave. In fact, the summation of the main wave and the reversible wave removes the harmful level of noise. Another type of AVC is one that works by producing a secondary sound field to interfere with the primary sound field destructively [1]. This technology is being concentrated by engineers for use in vehicles [2], marine and submarine [3, 4], and aircraft and space shuttles [5, 6]. They can cancel unwanted noise, and their size and weight are not huge; consequently, their application is practical and adaptable. One type of noise silencer is the Helmholtz resonator, which is divided into passive and adaptive types. The passive Helmholtz resonator can cancel the restricted range of frequency due to its constant internal volume and size. As stated, Helmholtz resonators are employed to decrease the transmitted sound from various acoustic systems, such as automobile exhausts, wind tunnels, and air ducts. They can reduce noise by reflecting sound to source. Dimensions of resonator is fixed with respect to the frequency of the sound source [7]. If the noise frequency of the source changes outside the aim range, the efficiency of the device reduces significantly. In contrast, the adaptive Helmholtz resonator changes the frequency of resonance adaptively by adjusting the volume or size of the hollow resonator to relieve noise level. Therefore, the tunable parameters, such as the volume of the resonator or the size of the orifice, must be controlled by an adaptive controller via a feedback signal. Real-time adaptive resonators can modify certain factors of their construction to face noise adequately depending on changes of noise frequency [8]. Commonly, feedback control approaches are used to tune the mechanical impedance of the resonator, and its performance depends on the accuracy of the closed-loop control system. Numerical simulations and conducted tests on a semi-active Helmholtz Resonator, SHR, were carried out [9-11]. They present theoretical model with ideal actuator controlled by analytical design.

Whereas adaptive Helmholtz resonator does not impose external sound energy to the main source, its construction is not complex, and energy consumption is very low. Some researchers focused on the adaptive Helmholtz resonators due to simplicity and high efficiency of that. The blade passage frequency tone of a fan was attenuated by utilizing an adjustable resonator which cavity length of that was changing [12, 13]. In addition, a continues tuning was suggested by using an electro-rheological fluid valve to adjust cross-sectional area of neck however control scheme was not explained [14]. In another investigation, a variable volume resonator was tested on the vehicle instead expansion muffler chamber. It was implemented to a piston which moved to change volume of resonator adaptively refer to engine revolution per minute [15]. Moreover, variable volume and changeable entrance neck of resonator was studied in sound reduction of engine [16, 17]. Furthermore, a patent was presented which tunable resonator includes both adjustable volume of cavity and neck's cross sectional of area by phase analyzing [18]. By increasing use of Origami shapes in mechanical engineering application, an adjustable resonator was introduced based origami structure which can changed its volume. To have optimum performance [19]. Using metamaterials and novel artificial material are developed in tunable resonators. A one-dimensional surface phononic crystal is studied in tunable resonator via finite element modelling [20]. Beside, tunable Helmholtz resonator based on metamaterial was employed for underwater applications [21]. Semi active resonator was developed and evaluated to provide wide range of efficiency, but that uses of air pressure sensor for measuring changes [22]. In another research, a semi active resonator is presented which has variable volume of resonator to produce energy rifling via that [23]. Moreover, recently based on Helmholtz resonator, some meta materials are developed to decrease sound intensity [24-28], due to its physical concept is proper to 3D printing. Sometimes, the sound power and frequency of that is variable permanently [29, 30], thus having a tool such as Helmholtz resonator can attenuate sound level by semi active method which is tunable by sound frequency automatically. Subsequently, based on this issue, having a system can adapt itself regards to sound frequency can be useful and efficient in industrial applications. Current study aims to develop an adaptive controller which tune gains to enhance performance of fabricated SHR by sound source differences via a simple variable orifice of resonator.

2. Methodology

As mentioned previously, the Helmholtz resonator functions as a mass-spring system, where the air inside of the cavity plays the role of spring, and air on the cavity neck (orifice) acts as a vibrating mass. By resonating, the sound level is diminished perfectly, while it works over a narrow frequency range near resonance frequency. Accordingly, to have a wider range, some parameters must be changed, referring to noise variations. It is similar to changing spring stiffness to have a different range of resonance. It can be exposed that the resonant frequency is given by:

$$f = \frac{v}{2\pi}\sqrt{\frac{A}{VL}} \tag{1}$$

where v is the velocity of sound, A is the neck area, L is the length of the air canal, and V is the cavity volume.

Hence, by changing parameters such as V, A, and L, the effective frequency of the resonator is changed. The present research aims to establish a variable cavity neck area mechanism to fabricate a semi-active Helmholtz resonator. Based on this idea, a butterfly orifice is mounted on the cavity neck, which can change its area, and a servomotor rotates it. Consequently, the servomotor can adjust the orifice area (cavity neck) by command signals. Referring to Equation 1, the resonant frequency is changed by the "A" parameter. To gain a better understanding, Figure 1 shows a schematic setup of this system. A hollow box of size 40×40×40 cm was made as a resonator and connected to the main tube. The diameter of the orifice was 8cm. A microphone connected to the PC receives the sound of the duct, and the PC can compute the sound level and its frequency. The place of microphone is fixed in the middle of the main tube to cancel the error of various experiments. This program is written using MATLAB/Simulink software and controls the rotation angle of the butterfly valve via the servomotor shaft, which is connected to an Arduino Uno board. Position control is applied for this purpose, and PWM is used for sending the desired position of the orifice butterfly to the servo motor. The experimental setup is illustrated in Figure 2. In the MATLAB/Simulink program shown in Figure 3, a buffer is used to gather the sound signal from the microphone. By utilizing the MATLAB function in Simulink and providing the code, the maximum sound and its corresponding frequency are identified. For this purpose, the Fast Fourier Transformation is employed, and the frequency of the maximum sound level is derived. In this way, the range of dominant frequency is reached, and the program changes the angle of the servomotor connected to the butterfly to 5 degrees for each 10 dB of sound intensity.

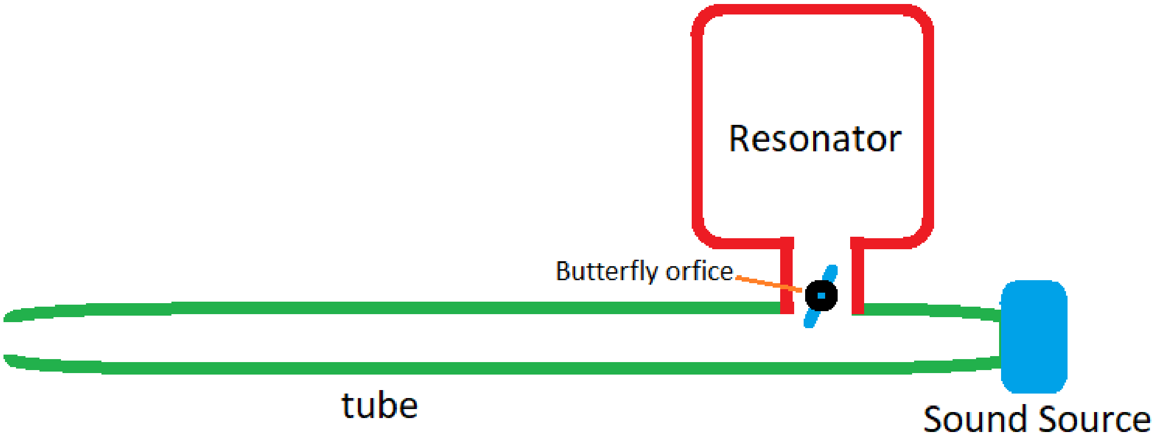
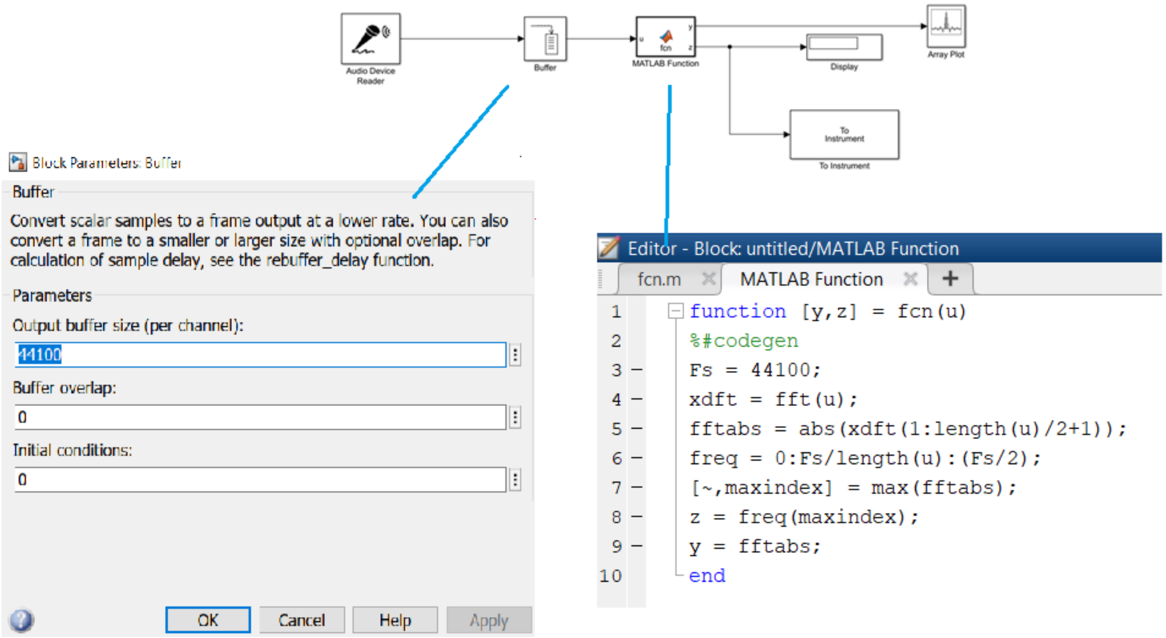


Fig. 1. Schematic configuration of semi-active Helmholtz Resonator

Fig. 2. The experimental setup a) Resonator b) Sound source c) Servomotor d) Butterfly and lever and f) Computer and MATLAB Software



Buffer

Convert scalar samples to a frame output at a lower rate. You can also convert a frame to a smaller or larger size with optional overlap. For calculation of sample delay, see the rebuffer_delay function.

Parameters

Output buffer size (per channel): 44100

Buffer overlap: 0

Initial conditions: 0

```
function [y,z] = fcn(u)
%#codegen
Fs = 44100;
xdft = fft(u);
fftabs = abs(xdft(1:length(u)/2+1));
freq = 0:Fs/length(u):(Fs/2);
[~,maxindex] = max(fftabs);
z = freq(maxindex);
y = fftabs;
end
```

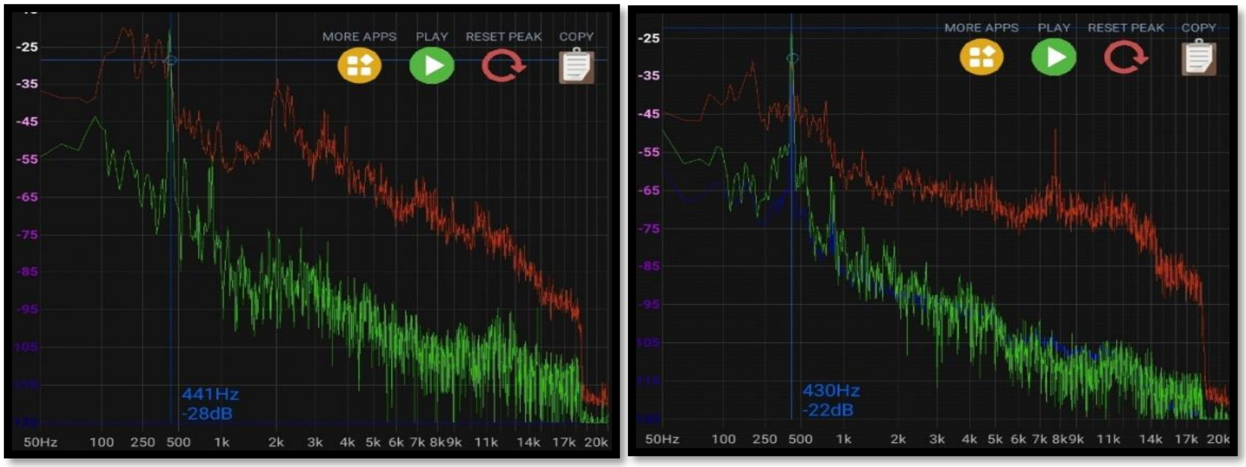
Fig. 1. Block diagram of MATLAB/Simulink for signal processing

In the first experiments, standard sounds are propagated through a sound speaker at the following frequencies: 440, 1000, 2000, 3000, and 4000 Hz. The semi-active Helmholtz Resonator (SHR) responds to them by changing the orifice area, and sound levels were measured at the end of the duct. Similarly, the experiment is repeated when the controller was deactivated for comparison with the activated controller. In all experiments, it is assumed that the flow velocity is constant and the volume of the resonator is fixed. The sound meter was initially calibrated by the Sound meter calibrator LUTRON SC-942.

In the second set of experiments, an air nozzle and a horn that works by airflow are mounted on the duct inlet as the noise source. Once again, measurements were taken in two states: when the controller was off and when it was on.

3. Result and discussion

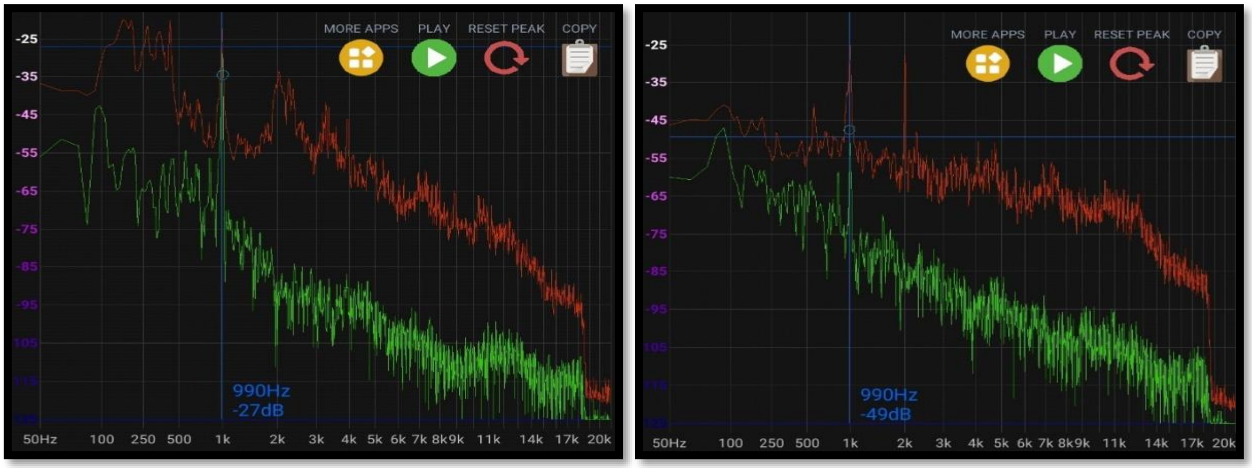
As mentioned in the previous part, SHR was tested when the controller was on and off. When sound propagated at the frequency of 440 Hz, when SHR was off, the sound level was -18 db. However, the SHR reduced the sound level to -22 dB when it was activated. Figure 4(a) reveals the diagram of sound levels by off, and Figure 4(b) shows the effect of the SHR when it is activated.



(a) (b)

Fig. 2. Sound level of duct when the SHR is off (a), and the SHR is on (b) (Blue line is average, and red and green lines are maximum and minimum, respectively.)

At the sound frequency of 1000 Hz, the sound reduction occurred from -27dB to -50dB when the SHR was working (Figure 4). The efficiency of the SHR is 46% in this case. Other frequency ranges above 1000 Hz did not show significant performance, as shown in Figure 5. In this figure, the comparison between two conditions for all cases is shown.



(a) (b)

Fig. 3. Level of sound measured in the duct when the SHR is off (a), and the SHR is on (b) (1000Hz) Blue line is average, and red and green lines are maximum and minimum, respectively.

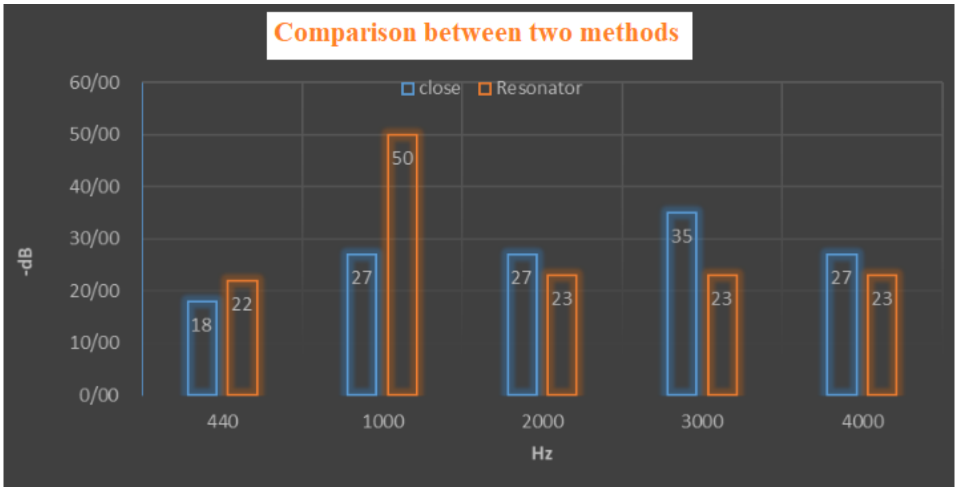
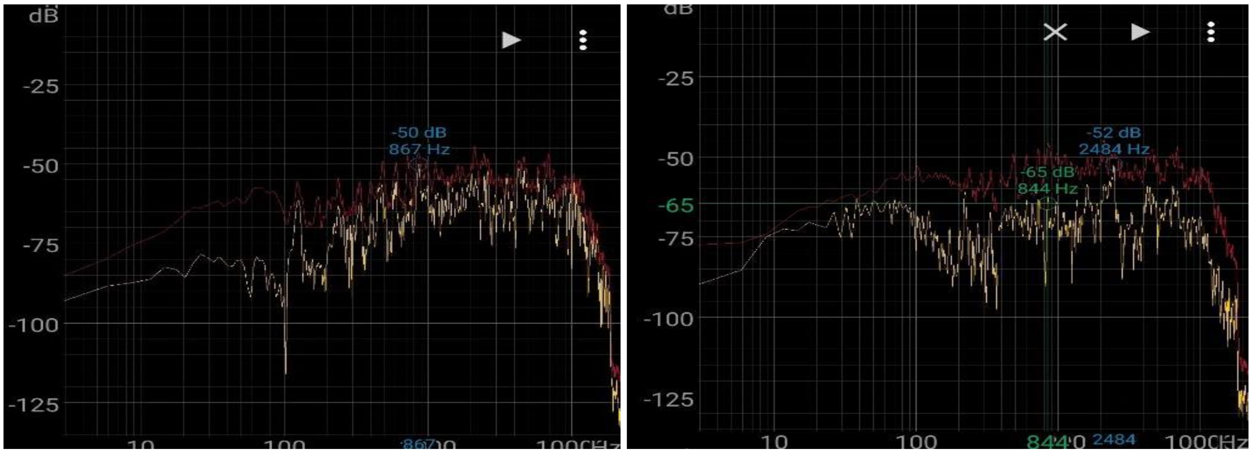


Fig. 4. The performance of SHR in low and high frequency (Blue: Controller is Off, Orange: Controller is On)

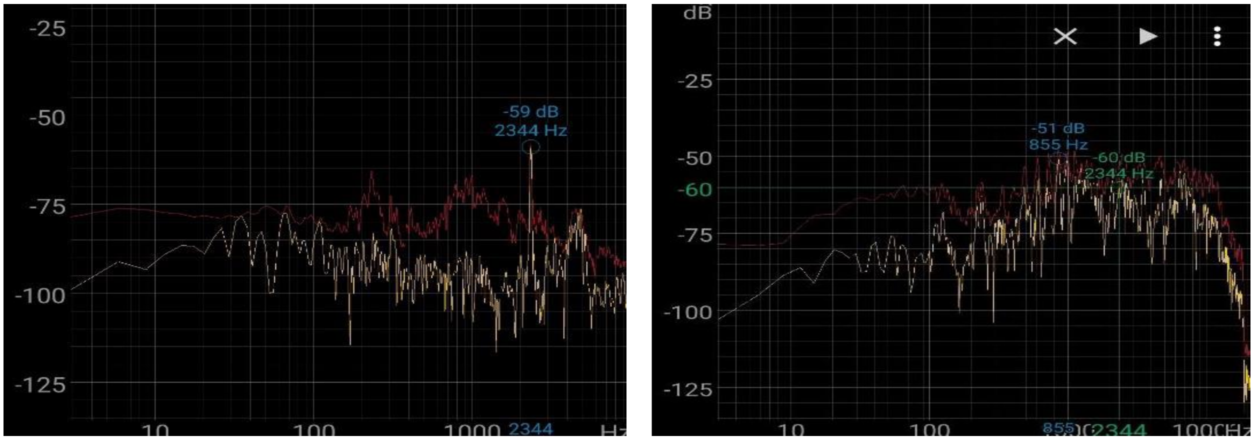
Moreover, an air nozzle was installed on the duct as a noise generator, which was connected to an air pump. Three levels of air pressure were exposed on the horn, which are low, medium, and high pressure. In the low level of air pressure, the sound level was -50 dB when the adaptive controller was off. As shown in Figure 7, activating the adaptive controller results in a decrease in sound level to -65 dB, which represents a 23% reduction in sound level.



(a) (b)

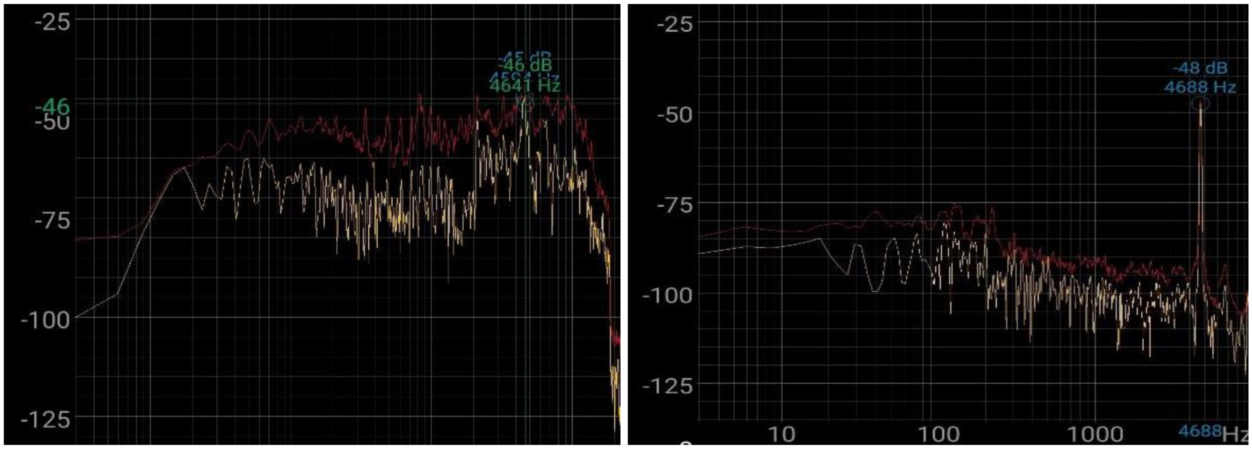
Fig. 5. Sound level of air flow in low level of air pressure: (a) resonator with off controller, (b) activated tunable resonator (Yellow line is minimum and red line is current value)

By inserting medium air pressure and high pressure into the duct, the sound level reduction is not as effective as that achieved with low pressure. At a medium airflow pressure, this reduction occurs from -59 dB to -60 dB, which can be seen in Figure 8. Similar to this case, at high pressure, the sound level reduction is not notable. As illustrated in Figure 9, the sound level by the adaptive resonator shows a decrease from -45 dB to -48 dB. While other studies have shown that sound resonators work effectively at low frequencies, when air pressure increases, the frequency of sound increases consequently.



(a) (b)

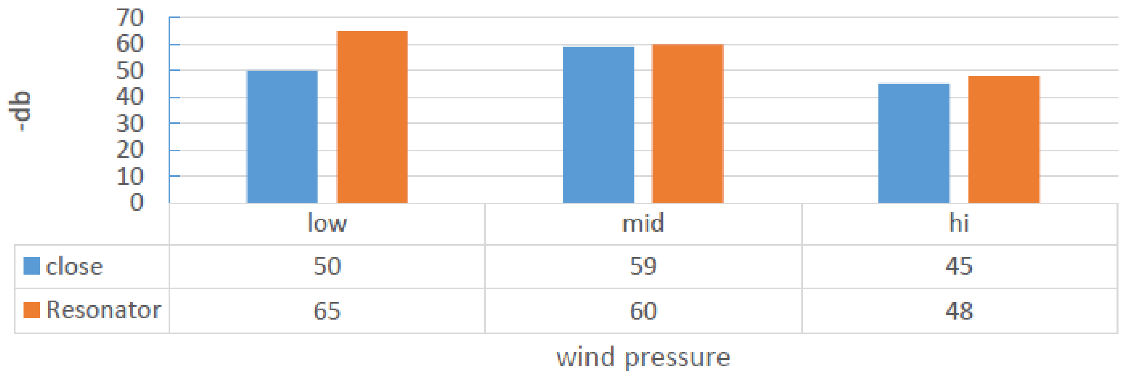
Fig. 8. Sound level of air flow in medium level of air pressure: (a) resonator with off controller, (b) activated tunable resonator



(a) (b)

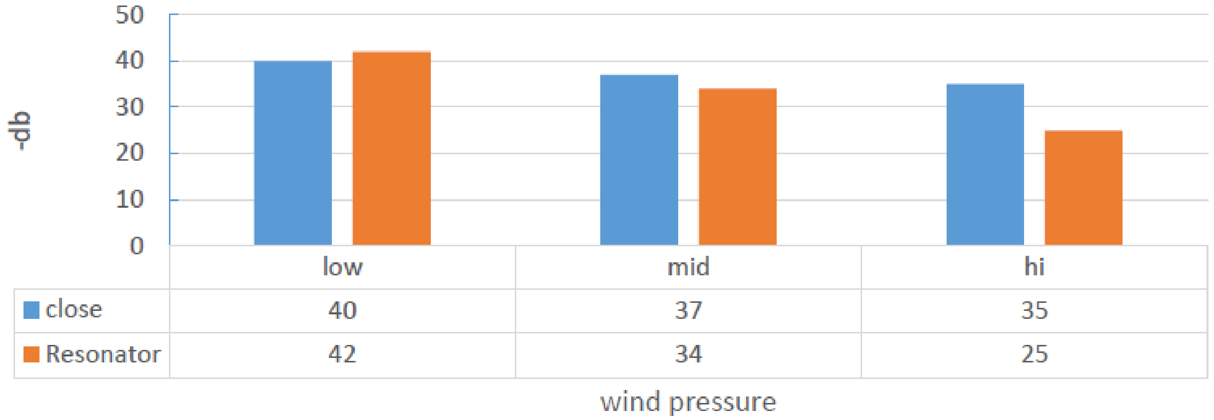
Fig. 9. Sound level of air flow in high level of air pressure: (a) resonator with off controller, (b) activated tunable resonator

Figure 10 shows the comparison between two cases at various air pressures. The findings may suggest that, at a low level of air pressure, the performance of a tunable Helmholtz resonator is better because the generated sound is in the low-frequency band. Similar to the previous set of experiments, the efficiency in this range is better than in the high-frequency range. Moreover, when one air horn was used as the sound source, the same results demonstrated better performance at low frequencies. This comparison is shown in Figure 11.



	low	mid	hi
🟦 close	50	59	45
🟧 Resonator	65	60	48

Fig. 10. The performance of SHR in low and high pressure (Blue: Controller is Off, Orange: Controller is On)



	low	mid	hi
🟦 close	40	37	35
🟧 Resonator	42	34	25

Fig. 11. The performance of SHR when sound source is air horn (Blue: Controller is Off, Orange: Controller is On)

Conclusion

An algorithm for tuning an adaptive Helmholtz resonator is presented to reach its optimal performance under variating environmental conditions and excitation noises. The strategy for tuning involves using a closed loop via a microphone, which sends current sound level to the control system. The controller adjusts the neck area of the resonator by a servomotor. Sound level reductions of 25 dB were achieved by combining a tunable resonator and a designed controller for this algorithm.

The experiments demonstrate that sound reduction at frequencies lower than 1000 Hz occurs effectively, with a decrease of approximately 46%. Furthermore, during a test with a pressurized tube connected to an air compressor, at low air pressure in the tube, SHR shows a 30% reduction in sound level, while at high pressure, the sound level reduction is 6.6%. Additionally, an air horn was tested as a sound source, which is connected to the tube. The unbearable sound level is diminished by 28.5% at a high level of air pressure, although there are no significant differences in pressure.

The main advantages of the semi-active resonator presented in this study are its simplicity of algorithm and low energy consumption for noise attenuation, compared to active noise controllers.

On the other hand, this presented system, compared to conventional passive systems, such as Helmholtz resonators, has the ability to maintain its performance at an optimal point due to tuning itself correspondingly by excitation noise variations in the low-frequency band. This can be used in utility units of oil and refinery centers or town border stations (TBS) for LPG/CNG to decrease sound level. Additionally, it is suggested to use adaptive controllers, such as Neural Network Controllers or Fuzzy Controllers, to achieve better performance.

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